Further Evaluation of Spray Characterization of Sprayers Typically Used in Vector Control

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14. ABSTRACT
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FURTHER EVALUATION OF SPRAY CHARACTERIZATION OF SPRAYERS TYPICALLY USED IN VECTOR CONTROL[3]

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ABSTRACT. This work reports droplet-size data measured as part of a collaborative testing program between the US Department of Agriculture, Agricultural Research Service, and the US Navy, Navy Entomological Center for Excellence. This is an ongoing relationship that seeks to test new and revised spray technologies that may potentially be used by deployed personnel. As new equipment comes to market or when existing equipment is modified they are all integrated into this annual testing. During the 2011 equipment evaluations, 24 sprayers were operated across their range of available settings (pressure and flow rate), using both water and oil solutions. Droplet-size data as measured with laser diffraction ranged from 4 to 223 μm (volume median diameter). Generally, as the spray rate increased, droplet size increased, and as the pressure increased at a given same spray rate, droplet size decreased. This information allows users to set up and operate these sprayers in a manner such that a particular droplet size is applied optimizing efficiency and efficacy of applications.

KEY WORDS Atomization, droplet size, sprayer, vector control, climate change

INTRODUCTION

In 2005 the US Department of Agriculture–Agricultural Research Service–Areawide Pest Management Research Unit–Aerial Application Technology group in College Station, Texas, and the US Navy–Navy Entomology Center of Excellence (NECE) in Jacksonville, FL, started a multiyear collaboration as part of the Department of Defenses' Deployed War-Fighter Protection Program. The testing or evaluation of operational safety, performance, and durability of pest management equipment used for vector control in domestic and international military operations as well as humanitarian efforts and on military installations is one of the primary missions of NECE. Equipment testing over the last several years included hand-held (Hoffmann et al. 2007b), truck-mounted (Hoffmann et al. 2007a), thermal foggers (Hoffmann et al. 2008), and ultra-low-volume (ULV) sprayers (Hoffmann et al. 2009).

Arthropod vectors, particularly mosquitoes, are primarily controlled through either ground or aerial applications of insecticides. Ultra-low-volume sprayers are typically used (Rathburn 1972, Linley and Jordan 1992, Matthews 1996, Rose 2001). When selecting equipment and insecticides, applicators depend on recommended operating parameters, as supplied by equipment manufacturers, along with spray rates and droplet sizes, as recommended by pesticide labels, to ensure the most efficacious application. For vector control space sprays, the applied droplet size should be less than 30 μm volume median diameter (VMD; $D_{V0.5}$) (Ledson and Matthews 1992; WHO 2006a, 2006b). Haile et al. (1982) found that the optimum droplet size for mosquito mortality was 7–22 μm, and Mount (1998) reported a range of 8–15 μm. Many vector control pesticide labels provide users with droplet-size requirements that generally fall between 8–30 μm $D_{V0.5}$ with at least 90% of the volume contained in droplets less than 50 μm. To comply with these labels, the user must select and/or adjust sprayers appropriately.

The objectives of the present work were to evaluate and report droplet-size data on available spraying equipment that are either already incorporated or could be incorporated into Department of Defense pest management programs using a methodology by which other similar systems can be evaluated to provide applicators with sprayer system performance data. The results provide operational guidance to meet label requirements by allowing program managers to select the best sprayers and operating parameters for their particular needs.

MATERIALS AND METHODS

A total of 215 replicated spray tests, comprising 24 sprayers and 2 solutions, were completed for this study. The sprayers were selected from ULV equipment commonly used for vector control applications. The specific testing protocol, spray

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formulations, and equipment tested are discussed in the following sections.

Droplet-size measurements

Each combination of sprayer and spray formulation had a minimum of 3 independent replicated measurements taken. For each replication, a Sympatec laser system (Sympatec Inc., Clausthal, Germany) was positioned approximately 2 m from the outlet of the sprayer. The spray cloud was directed through the laser beam for 10–20 sec, during which time droplet-size measurements of the spray cloud were made. The time that the spray cloud was directed through the optical path of the laser varied between sprayers depending on the width of the spray plume generated. For each replication, the entire spray plume was measured (ASTM 2005). Appropriate personal protective equipment, including respirators, gloves, goggles, and Tyvex suits, were worn during all tests containing active ingredients.

Droplet-sizing system

The Sympatec Helos system uses a 623 nm He-Ne laser and was fitted with an R5 lens, making the dynamic size range from 0.5 to 875 μm in 32 sizing bins. These evaluations were conducted outdoors and around equipment with excessive vibration, which resulted in measurements, including an artificial "spike" in the size data due to signal interference in the last, largest droplet-size measurement channel. This channel was turned off to prevent this spiking, modifying the dynamic range of the instrument to 0.5–735 μm. The final measured droplet size was not affected as no droplets were detected within 2 sizing bins (droplets greater than 515 μm).

Means and standard deviations of the $D_{V0.5}$, $D_{V0.1}$, and $D_{V0.9}$ were determined for each combination of sprayer and spray formulation. The $D_{V0.5}$ is the droplet diameter (μm) where 50% of the spray volume is contained in droplets smaller than this value (ASTM 2004). Similarly, the $D_{V0.1}$ and $D_{V0.9}$ values are the diameters at which 10% and 90%, respectively, of the spray volume is contained in droplets of this size or less. The mean relative span (RS) (Eq. 1), which is a dimensionless measure of the spread of the droplet distribution, was also determined as follows:

$$RS = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}}. \qquad (1)$$

Smaller RSs are indicative of a sprayer producing a narrow spray distribution, i.e., larger span between the 10% and 90% spray-volume diameter. Conversely, RSs are indicative of wider spray size distributions.

Spray formulations

Two spray formulations were used in the droplet-size evaluations:

1. BVA 13 ULV Oil (Severely Hydro-treated Paraffinic Oil, ADAPCO, Sanford, FL).
2. Water with 0.25% volume/volume addition of a nonionic surfactant (NIS) (R-11, Wilbur-Ellis Co., San Antonio, TX).

Equipment

Descriptions of the equipment tested are given below. The descriptions include the name and manufacturer, followed by the general operational information and sprayer dimensions. Note that all equipment characteristics are as given by the manufacturer, unless otherwise noted. Specific nozzle information is supplied only if the setup tested differed from the standard configuration. Additional operational information can be obtained from the respective manufacturers.

- *ADAPCO Guardians* (ADAPCO, Sanford, FL) are truck-mounted sprayers that create spray droplets by directing high-speed air, which is generated by a gasoline-engine–powered blower, across the nozzle.
  - *55 ES*: A truck-mounted sprayer with a maximum flow rate of 7 oz/min (591 ml/min).
  - *95 ES*: A truck-mounted sprayer with a maximum flow rate of 20 oz/min (591 ml/min).
  - *190 ES*: A truck-mounted sprayer with a maximum flow rate of 24 oz/min (710 ml/min).
- *B&G Phoenix* (B&G Chemicals & Equipment Co., Dallas, TX) sprayers also utilize a gasoline-powered engine to drive a blower to provide high-speed air shear atomization at the spray nozzle.
  - *230 H*: A handheld sprayer with a maximum flow rate of 8 oz/min (237 ml/min).
  - *480 Diesel*: A truck-mounted sprayer with a maximum flow rate of 16 oz/min (473 ml/min).
  - *680 MD*: A truck-mounted sprayer with a maximum flow rate of 18 oz/min (532 ml/min).
- *Buffalo Turbine Model CSM2 Mist Sprayer* (Buffalo Turbine, Springville, NY): A truck/trailer sprayer with a maximum flow rate of 10 gal/min (37.9 liters/min). Testing was conducted using an experimental rotary nozzle in place of the standard flat fan nozzles.
- *Clarke* (Clarke Mosquito Control, Roselle, IL) sprayers also utilize gasoline-engine

Table 1. Droplet-size data for sprayers tested with water + nonionic surfactant solution.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (µm ± SD)	$D_{V0.5}$ (µm ± SD)	$D_{V0.9}$ (µm ± SD)	Relative span
Curtis Dyna-Fog	6/41	4/148	8.29 ± 0.16	15.38 ± 0.13	27.74 ± 0.21	1.26
Maxi-Pro 2D	6/41	24/710	11.08 ± 0.13	25.84 ± 0.63	55.44 ± 1.14	1.72
ULV	6/41	50/1,480	14.48 ± 0.33	42.21 ± 1.48	101.93 ± 3.59	2.07
ADAPCO Guardian 55 ES ULV	100/690	3.8/112	9.26 ± 0.13	28.53 ± 0.98	65.93 ± 3.54	1.99
Buffalo Turbine	0	7/207	39.64 ± 0.87	96.21 ± 2.46	175.62 ± 7.82	1.41
Model CSM2 with rotary nozzle	0	50/1,480	101.17 ± 2.50	222.80 ± 7.80	342.16 ± 5.03	1.08
Curtis Dyna-Fog Twister XL3	0	4/148	10.99 ± 0.37	22.79 ± 0.29	36.87 ± 0.37	1.14
Stihl SR 420/0.5 nozzle	0	4/148	23.24 ± 0.46	67.61 ± 0.35	131.38 ± 5.47	1.60
Stihl SR 420/0.8 nozzle	0	13/385	26.25 ± 0.78	74.88 ± 0.28	134.97 ± 2.57	1.45
IGEBA TF 35	0	10.7/317	18.53 ± 1.40	38.32 ± 2.54	64.82 ± 5.66	1.21

driven–blowers to provide high air shear atomization at the nozzle.

- *Cougar*: A truck-mounted sprayer with a maximum flow rate of 18 oz/min (500 ml/min).
- *Clarke Grizzly*: A truck-mounted sprayer with a maximum flow rate of 18 oz/min (500 ml/min). A portion of the evaluations were conducted by replacing the standard nozzle with a LECO shear nozzle.

- *Curtis Dyna-Fog®* (Curtis Dyna-Fog, Westfield, IN): Similar to previous sprayers, a gasoline engine is used to drive a blower that provides high-speed air at the nozzle for atomization of the spray stream. The only exceptions in the list below are the *Blackhawk 2620* and *Falcon 4000*, which are thermal foggers.
  - *AG-Mister LV-8*: A truck-mounted sprayer with a maximum flow rate of 2.2 gal/min (8.4 liters/min).

Table 2. Droplet-size data for sprayers tested across complete operational ranges with water + nonionic surfactant solution.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (µm ± SD)	$D_{V0.5}$ (µm ± SD)	$D_{V0.9}$ (µm ± SD)	Relative span
London Fog	0	4/148	2.31 ± 0.22	9.33 ± 0.77	22.07 ± 2.04	2.12
XKD		8/237	6.84 ± 1.10	17.07 ± 0.80	47.46 ± 2.86	2.38
		16/473	10.11 ± 1.64	26.62 ± 1.37	57.89 ± 3.84	1.79
London Fog	4/28	4/148	7.61 ± 0.23	14.57 ± 0.18	24.75 ± 0.12	1.18
18–20		8/237	8.34 ± 0.07	17.12 ± 0.05	29.64 ± 0.17	1.24
		16/473	7.44 ± 0.44	18.43 ± 0.21	33.90 ± 0.47	1.44
Clarke Grizzly	4/28	4/148	9.86 ± 0.13	18.17 ± 0.12	29.80 ± 0.18	1.10
with LECO		12/355	10.51 ± 0.14	22.45 ± 0.16	40.01 ± 0.25	1.31
Head		20/592	10.93 ± 0.13	23.45 ± 0.11	42.39 ± 0.38	1.34
	6/41	4/148	7.51 ± 0.47	14.32 ± 0.59	24.49 ± 0.72	1.19
		12/355	8.47 ± 0.11	16.60 ± 0.52	28.71 ± 0.86	1.22
		20/592	8.98 ± 0.10	16.92 ± 0.18	28.83 ± 0.36	1.17
Clarke Grizzly	6/41	1/30	9.61 ± 2.47	19.39 ± 0.88	33.45 ± 0.38	1.23
		4/148	6.41 ± 2.51	19.29 ± 1.08	34.51 ± 0.53	1.46
		8/237	9.74 ± 0.66	20.36 ± 0.03	36.15 ± 0.35	1.30
		12/355	9.89 ± 1.14	20.83 ± 0.40	36.99 ± 0.41	1.30
		16/474	10.61 ± 0.16	21.50 ± 0.02	39.26 ± 0.39	1.33
		18/533	10.27 ± 0.33	21.59 ± 0.13	39.75 ± 0.17	1.37
		20/592	4.20 ± 0.33	20.20 ± 0.19	38.31 ± 0.18	1.69
	4/28	1/30	10.48 ± 0.96	28.39 ± 0.43	48.86 ± 0.96	1.35
		4/148	11.08 ± 3.60	28.55 ± 0.57	49.41 ± 0.84	1.34
		8/237	4.05 ± 0.61	28.15 ± 0.65	51.89 ± 0.89	1.70
		12/355	3.03 ± 0.06	26.79 ± 0.17	51.60 ± 0.40	1.81
		16/474	5.27 ± 1.13	28.22 ± 0.54	53.22 ± 1.08	1.70
		18/533	6.58 ± 0.25	28.63 ± 0.22	53.17 ± 0.60	1.63
		20/592	9.40 ± 0.88	29.16 ± 0.16	53.69 ± 0.60	1.52

Table 3. Droplet-size data for sprayers tested with BVA 13 oil.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Relative span
Curtis Dyna-Fog Maxi-Pro 2D ULV	6/41	4/28	1.43 ± 0.21	5.29 ± 1.27	15.24 ± 1.15	2.61
		24/710	10.19 ± 0.23	29.02 ± 0.34	59.23 ± 0.82	1.69
		50/1,480	6.33 ± 1.00	13.31 ± 0.85	27.10 ± 1.26	1.56
ADAPCO Guardian 55 ES	100/690	3.8/112	5.85 ± 0.54	25.34 ± 2.21	62.81 ± 6.18	2.25
Buffalo Turbine Model CSM2 with rotary nozzle	0	4/28	47.40 ± 1.39	102.98 ± 4.93	160.31 ± 9.75	1.10
		30/888	100.84 ± 18.18	218.53 ± 31.79	319.48 ± 37.82	1.00
Curtis Dyna-Fog Twister XL3	0	4/28	8.67 ± 0.40	20.78 ± 1.19	40.16 ± 1.85	1.52
Stihl SR 420/0.5 nozzle	0	4/28	13.51 ± 1.09	49.98 ± 1.38	116.38 ± 3.82	2.06
Stihl SR 420/0.8 nozzle		13/385	15.48 ± 0.18	60.93 ± 1.16	127.57 ± 3.12	1.84
IGEBA TF 35	0	10.7/317	1.17 ± 0.09	3.85 ± 0.42	14.04 ± 9.67	3.35
Curtis Dyna-Fog Blackhawk 2620	0	20/592	1.15 ± 0.05	3.76 ± 0.25	8.10 ± 0.84	1.85

- *Maxi-Pro 2D*: A truck-mounted sprayer with a maximum flow rate of 128 oz/min (3.8 liters/min).
- *Typhoon 2D*: A truck-mounted sprayer with a maximum flow rate of 128 oz/min (3.8 liters/min).
- *Twister* XL3: A backpack sprayer with a maximum flow rate of 17 oz/min (503 ml/min).
- *Blackhawk Model 2620*: A hand-held thermal fogger with a maximum flow rate of 38 oz/min (1125 ml/min).

Table 4. Droplet-size data for sprayers tested across complete operational ranges with BVA 13 oil.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/mil/min)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Relative span
London Fog XKD	6/41	4/148	1.64 ± 0.03	6.53 ± 0.11	16.81 ± 0.66	2.32
		8/237	3.04 ± 0.09	13.79 ± 0.49	35.25 ± 0.88	2.34
		16/473	4.44 ± 0.01	25.47 ± 0.85	64.53 ± 4.97	2.36
London Fog 18–20	4/28	4/148	1.58 ± 0.12	6.25 ± 0.58	15.96 ± 0.62	2.30
		8/237	3.44 ± 0.64	10.98 ± 0.39	21.75 ± 0.03	1.67
		16/473	4.42 ± 0.32	13.66 ± 0.44	26.63 ± 0.48	1.63
Clarke Grizzly with LECO Head	4/28	4/148	6.18 ± 1.96	13.93 ± 0.80	25.86 ± 0.68	1.41
		12/355	4.22 ± 0.24	18.23 ± 0.56	35.89 ± 0.59	1.74
		20/592	4.35 ± 0.09	19.55 ± 0.36	37.89 ± 0.75	1.72
	6/41	4/148	3.20 ± 0.28	10.03 ± 0.20	18.68 ± 0.27	1.54
		12/355	6.02 ± 0.86	13.91 ± 0.73	26.22 ± 1.15	1.45
		20/592	5.98 ± 0.23	14.52 ± 0.14	27.68 ± 0.15	1.49
B&G Phoenix Fogger MD 680	6/41	1/30	1.53 ± 0.02	5.82 ± 0.15	12.60 ± 0.31	1.90
		4/148	3.46 ± 0.93	9.39 ± 0.42	16.70 ± 0.28	1.41
		8/237	6.42 ± 0.71	12.41 ± 0.21	22.57 ± 0.45	1.30
		16/474	6.23 ± 0.07	17.80 ± 0.25	37.57 ± 0.66	1.76
Clarke Grizzly	4/28	1/30	2.23 ± 0.07	13.62 ± 0.23	32.67 ± 0.07	2.24
		4/148	2.69 ± 0.06	15.02 ± 0.54	34.30 ± 0.61	2.10
		8/237	3.03 ± 0.25	18.17 ± 1.13	38.86 ± 1.85	1.97
		12/355	3.53 ± 0.08	20.68 ± 0.31	43.65 ± 0.71	1.94
		16/474	3.72 ± 0.21	21.79 ± 0.45	45.32 ± 0.48	1.91
		18/533	3.49 ± 0.19	21.29 ± 0.30	44.08 ± 0.75	1.91
		20/592	3.84 ± 0.15	21.92 ± 1.02	45.21 ± 1.79	1.89
	6/41	1/30	2.93 ± 1.85	10.72 ± 3.40	26.17 ± 3.74	2.17
		4/148	2.35 ± 0.04	10.62 ± 0.11	24.66 ± 0.22	2.10
		8/237	2.43 ± 0.08	11.60 ± 0.28	27.30 ± 0.37	2.14
		12/355	3.08 ± 0.32	14.12 ± 1.01	30.52 ± 1.31	1.94
		16/474	3.31 ± 0.04	15.22 ± 0.49	32.90 ± 1.91	1.95
		18/533	3.56 ± 0.06	15.41 ± 0.08	32.28 ± 0.24	1.86
		20/592	3.68 ± 0.05	15.99 ± 0.17	33.39 ± 0.25	1.86

Table 5. Droplet-size data for sprayers tested with water + nonionic surfactant solution.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Relative span
Spectrum 3D Surface Sanitizer	75/517	7.7/228	77.93 ± 8.33	125.09 ± 8.42	176.15 ± 2.58	0.79
Stihl SR 420 w/ Spectrum ES	—	—	32.04 ± 2.95	86.87 ± 5.56	159.14 ± 7.66	1.47
Spectrum 4010 MD Diesel ES	30/207	26/770	35.93 ± 0.73	96.21 ± 0.21	170.64 ± 5.83	1.40
	34/234	77/2,279	44.49 ± 0.64	117.20 ± 1.46	217.57 ± 6.71	1.48
	40/276	180/5,328	45.87 ± 0.93	124.75 ± 3.16	249.84 ± 3.68	1.64
B&G Phoenix 230 Handheld ULV Fogger	4.5/31	1.35/40	8.89 ± 1.80	21.63 ± 0.66	40.31 ± 1.85	1.45
		4/118	5.89 ± 0.37	23.46 ± 0.41	44.37 ± 0.66	1.64
		8/237	9.20 ± 0.91	29.37 ± 0.77	56.74 ± 1.26	1.62
Curtis Dyna-Fog Typhoon 2D Diesel	—	8/237	6.67 ± 1.20	13.28 ± 1.41	23.52 ± 1.83	1.27
		16/474	8.43 ± 0.41	19.05 ± 1.25	37.07 ± 2.93	1.50
Curtis Dyna-Fog AG Mister LV-8 Two Nozzles	6/41	128/3,789	24.62 ± 1.05	70.87 ± 1.44	164.32 ± 9.45	1.97
Curtis Dyna-Fog AG Mister LV-8 Four Nozzles	6/41	128/3,789	20.08 ± 0.73	58.68 ± 3.61	125.86 ± 9.30	1.80
Curtis Dyna-Fog AG Mister LV-8 Eight Nozzles	6/41	128/3,789	18.21 ± 1.48	53.50 ± 2.71	106.44 ± 2.75	1.65
Curtis Dyna-Fog AG Mister LV-8 Two Nozzles	6/41	288/3,789	27.33 ± 0.39	74.31 ± 2.16	166.82 ± 18.67	1.87
Curtis Dyna-Fog AG Mister LV-8 Four Nozzles	6/41	288/3,789	25.82 ± 1.83	73.43 ± 5.61	153.75 ± 10.90	1.74
Curtis Dyna-Fog AG Mister LV-8 Eight Nozzles	6/41	288/3,789	22.39 ± 3.26	66.48 ± 6.03	143.58 ± 6.57	1.83
DAT U-BLAS-ONE Backpack ULV	—	3.4/101	7.62 ± 0.12	20.16 ± 1.01	36.23 ± 1.53	1.42

  - *Falcon Model* 4000: A hand-held thermal fogger with a maximum flow rate of 23.5 oz/min (695 ml/min).
- *DAT U-BLAS-ONE Backpack Sprayer with ULV Nozzle* (Dorendorf Advanced Technologies (DAT), Winnebago, MN) is a backpack sprayer with a maximum flow rate of 12 oz/min (355 ml/min).
- *IGEBA TF 35* (Weitnau, Germany) is a hand-held thermal fogger with a maximum flow rate of 23.5 oz/min (695 ml/min).
- *London Fog* (London Fog, Long Lake, MN) sprayer also utilizes engine-driven blowers to provide for high-speed air shear atomization at the nozzle.
  - *18–20*: A truck-mounted sprayer with a maximum flow rate of 20 oz/min (592 ml/min).
  - *XKD*: A truck-mounted ULV sprayer with a maximum flow rate of 10 oz/min (256 ml/min).
- *Spectrum* (Spectrum Electrostatic Sprayers, Houston, TX) sprayers also utilize engine-driven blowers for air shear atomization. These sprayers also provide an electrostatic charge on the resulting spray droplets.
  - *4010* MD: A truck-mounted sprayer with a maximum flow rate of 3.5 gal/min (13 l/min).
  - *3D Electrostatic Sprayer*: A wheeled-cart–mounted sprayer with a maximum flow rate of 8.0 oz/min (242 ml/min).
- *STIHL Backpack Sprayer and Duster, Model SR 420*: A backpack sprayer with a maximum flow rate of 102 oz/min (3 liters/min). Additional testing was done on this spray with the standard spray nozzle being replaced with a Spectrum electrostatic nozzle.

Statistical analyses

Given that the objective of this study was not to rank or statistically separate the sprayers; no means separation was performed. The means and the standard deviations of the measured droplet-size parameters are presented.

RESULTS

The droplet-size results for all sprayers, sprayer settings, and spray solutions tested are given in Tables 1–8. More detailed observations of the data follow in the upcoming text.

Table 6. Droplet-size data for sprayers tested across complete operational ranges with water + nonionic surfactant solution.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (µm ± SD)	$D_{V0.5}$ (µm ± SD)	$D_{V0.9}$ (µm ± SD)	Relative span
ADAPCO Guardian 95ES ULV	4/28	4/118	7.39 ± 2.39	23.09 ± 0.83	42.53 ± 0.56	1.52
		6/178	6.62 ± 0.10	17.69 ± 0.35	34.49 ± 1.05	1.58
		8/237	7.16 ± 0.06	21.41 ± 0.20	40.56 ± 0.41	1.56
		12/355	7.70 ± 0.18	24.09 ± 0.25	47.22 ± 0.55	1.64
		16/474	8.48 ± 0.06	25.62 ± 0.18	54.26 ± 0.58	1.79
		20/592	9.02 ± 0.35	27.25 ± 0.74	58.96 ± 0.41	1.83
	6/41	8/237	6.57 ± 0.05	16.61 ± 0.23	31.52 ± 0.55	1.50
		12/355	6.55 ± 0.11	17.99 ± 0.22	35.23 ± 0.44	1.59
		16/474	7.33 ± 0.03	20.73 ± 0.23	42.91 ± 0.68	1.72
		20/592	7.42 ± 0.04	20.85 ± 0.25	44.57 ± 0.34	1.78
ADAPCO Guardian 55ES ULV						
Nozzle 20	80/552	1.3/38	2.22 ± 0.26	11.56 ± 1.49	36.14 ± 4.92	2.93
Nozzle 30		2.5/74	5.24 ± 0.49	19.48 ± 1.34	49.47 ± 2.89	2.27
Nozzle 40		3.8/112	4.82 ± 0.40	17.08 ± 1.21	40.56 ± 2.95	2.09
Nozzle 51		3.8/112	5.03 ± 0.14	23.33 ± 0.51	55.11 ± 1.51	2.15
Nozzle 61		6.9/204	7.09 ± 0.76	27.60 ± 1.70	63.98 ± 3.65	2.06
Nozzle 20	100/689	1.3/38	3.34 ± 0.35	13.24 ± 1.39	33.90 ± 5.94	2.30
Nozzle 30		2.5/74	6.25 ± 0.91	21.58 ± 2.64	53.41 ± 7.42	2.18
Nozzle 40		3.8/112	6.96 ± 0.49	23.03 ± 0.20	56.63 ± 0.61	2.16
Nozzle 51		3.8/112	5.29 ± 0.76	23.99 ± 2.17	58.83 ± 4.99	2.23
Nozzle 61		6.9/204	7.57 ± 0.32	28.46 ± 0.84	68.48 ± 2.21	2.14
B&G Phoenix 480 Diesel ULV Fogger	3.5/24	1/30	3.44 ± 0.68	23.01 ± 0.54	43.76 ± 0.54	1.75
		4/118	9.31 ± 0.07	26.37 ± 0.25	48.17 ± 0.38	1.47
		8/237	9.63 ± 0.23	31.46 ± 0.35	57.84 ± 0.63	1.53
		10/296	9.70 ± 1.12	34.50 ± 0.45	62.23 ± 0.52	1.52
		16/474	16.30 ± 0.41	42.24 ± 0.54	77.69 ± 2.68	1.45
	4.5/31	1/30	5.79 ± 0.79	18.03 ± 0.53	34.77 ± 0.56	1.61
		4/118	8.01 ± 0.71	21.10 ± 0.24	38.38 ± 0.38	1.44
		8/237	7.03 ± 0.48	25.49 ± 0.18	46.39 ± 0.44	1.54
		10/296	6.79 ± 0.33	27.27 ± 0.82	50.06 ± 1.56	1.59
		16/474	11.82 ± 0.51	34.61 ± 0.42	63.53 ± 1.12	1.49
ADAPCO Guardian 190ES	4/28	8/237	7.13 ± 0.06	22.92 ± 0.09	43.92 ± 0.34	1.60
		12/355	7.08 ± 0.20	22.62 ± 0.31	44.50 ± 1.71	1.65
		16/474	7.58 ± 0.26	22.48 ± 0.03	43.57 ± 0.51	1.60
	6/41	8/237	5.32 ± 0.02	12.65 ± 0.15	24.05 ± 0.28	1.48
		12/355	5.33 ± 0.31	12.56 ± 0.10	23.96 ± 0.23	1.48
		16/474	5.72 ± 0.06	12.86 ± 0.09	24.72 ± 0.98	1.48
Clarke Cougar Cold Aerosol Generator	7.5/52	1/30	8.57 ± 0.30	19.01 ± 0.49	34.03 ± 1.09	1.34
		4/118	9.28 ± 0.41	19.13 ± 0.16	34.72 ± 0.43	1.33
		8/237	8.54 ± 0.05	20.79 ± 0.21	37.14 ± 0.28	1.38
		12/355	8.38 ± 0.15	21.73 ± 0.32	39.73 ± 0.89	1.44
		16/474	8.22 ± 0.30	23.16 ± 0.56	42.89 ± 0.96	1.50
		18/533	8.29 ± 0.09	24.25 ± 0.41	45.19 ± 0.92	1.52

Water + 0.25% v/v nonionic surfactant sprays

The VMDs across all sprayers tested with the water and NIS spray solution ranged from 9 to 223 µm, with the majority of the sprayers having VMDs between 15 and 35 µm (Tables 1, 2, 5, and 6). For those sprayers whose settings could be modified, there were general trends in the atomization data observed. Typically, as the flow rate increased for a given sprayer, the droplet size also increased as a result of less air shear energy per volume of spray material available for atomization at constant pressure. However, this trend was not always present. The Clarke Grizzly sprayer without the LECO head maintained a constant VMD across the full range of flow rates for each pressure tested with only slight increases in the $D_{V0.9}$ at higher flow rates. It should be noted that the Curtis Dyna-Fog AG Mister LV-8 did show a trend of smaller droplet size with lower per-nozzle spray rate (Table 5). The overall spray rate remained the same, but the number of nozzles used was increased from 2 to 8, which decreased the per-nozzle spray rate as well as the resulting VMD. For sprayers whose pressure could be changed, increases in spray pressure generally increased droplet size if the flow rate could not be independently controlled. However, this trend also did not hold for all sprayers as both the B&G Phoenix 480 Diesel ULV Fogger

Table 7. Droplet-size data for sprayers tested with BVA 13 oil solution.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Relative span
B&G Phoenix Model 230 Handheld ULV Fogger	4.5/31	0.67/20	2.62 ± 0.16	13.16 ± 0.59	33.45 ± 0.60	2.34
		5.2/154	3.55 ± 0.13	24.13 ± 0.31	52.76 ± 0.82	2.04
Curtis Dyna-Fog Typoon 2D Diesel Aerosol Applicator	—	8/237	3.65 ± 0.62	14.54 ± 2.10	58.26 ± 16.12	3.71
		16.9/500	5.47 ± 2.06	23.81 ± 4.33	56.69 ± 14.40	2.14
Curtis Dyna-Fog Falcon Model 4000 Thermal Fog Applicator	—	3.4/101	1.11 ± 0.00	3.56 ± 0.01	7.47 ± 0.02	1.79
DAT U-BLAS-ONE Backpack Sprayer with ULV Nozzle	—	3.4/101	4.75 ± 0.36	14.20 ± 0.41	27.77 ± 0.88	1.62

Table 8. Droplet-size data for sprayers tested across complete operational ranges with BVA 13 oil.

Sprayer	Pressure (psi/kPa)	Flow rate (oz/min/ml/min)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Relative span
ADAPCO Guardian 95ES ULV	4/28	4/118	2.69 ± 0.14	11.86 ± 0.33	26.49 ± 0.52	2.01
		8/237	2.44 ± 0.14	14.54 ± 0.32	31.57 ± 0.24	2.00
		12/355	2.92 ± 0.08	16.15 ± 0.19	33.42 ± 0.42	1.89
		16/474	3.67 ± 0.07	20.93 ± 0.25	42.04 ± 0.44	1.83
		20/592	4.45 ± 0.27	22.23 ± 0.80	45.74 ± 2.84	1.86
	6/41	4/118	1.96 ± 0.17	8.48 ± 0.85	21.04 ± 1.69	2.25
		8/237	2.28 ± 0.03	10.42 ± 0.16	24.18 ± 0.38	2.10
		12/355	3.17 ± 0.12	13.78 ± 0.10	28.49 ± 0.02	1.84
		16/474	3.70 ± 0.11	16.10 ± 0.09	32.27 ± 0.11	1.77
		20/592	3.86 ± 0.10	18.25 ± 0.28	36.22 ± 0.29	1.77
ADAPCO Guardian 55ES ULV	80/552	1.4/41	2.08 ± 0.21	9.03 ± 1.12	25.31 ± 3.38	2.57
		2.6/77	2.50 ± 0.19	11.12 ± 0.34	30.09 ± 0.65	2.48
		3.8/112	3.83 ± 0.40	16.35 ± 0.29	40.34 ± 1.11	2.23
		5.4/160	4.61 ± 0.54	22.35 ± 0.51	52.18 ± 0.83	2.13
		4.6/136	4.90 ± 0.56	19.78 ± 0.29	47.43 ± 1.14	2.15
	100/689	1.4/41	2.00 ± 0.18	8.65 ± 0.79	24.69 ± 1.78	2.63
		2.6/77	3.54 ± 0.85	15.76 ± 0.54	44.12 ± 1.73	2.58
		3.8/112	4.22 ± 0.24	20.92 ± 0.79	53.62 ± 1.37	2.36
		5.4/160	5.29 ± 0.79	26.43 ± 0.86	62.83 ± 1.63	2.18
		4.6/136	7.66 ± 1.16	32.55 ± 0.90	71.99 ± 1.48	1.98
B&G Phoenix 480 Diesel ULV Fogger	3.5/24	1/30	2.50 ± 0.13	12.66 ± 0.29	32.88 ± 0.37	2.40
		4/118	3.35 ± 0.04	19.46 ± 0.23	41.52 ± 0.24	1.96
		8/237	3.83 ± 0.02	22.98 ± 0.30	46.06 ± 0.58	1.84
		13.2/391	5.89 ± 0.90	28.81 ± 1.11	63.59 ± 5.97	2.00
	4.5/31	1/30	2.39 ± 0.04	10.54 ± 0.11	26.04 ± 1.53	2.24
		4/118	3.41 ± 0.03	17.07 ± 0.14	35.59 ± 0.42	1.89
		8/237	3.79 ± 0.06	21.30 ± 0.28	42.51 ± 0.41	1.82
		13.2/391	4.29 ± 0.14	24.47 ± 0.15	50.11 ± 1.64	1.87
ADAPCO Guardian 190ES ULV	4/28	8/237	5.08 ± 0.20	13.05 ± 0.14	25.19 ± 0.55	1.54
		12/355	5.37 ± 0.19	13.00 ± 0.09	24.73 ± 0.36	1.49
		16/474	6.24 ± 0.12	14.21 ± 0.11	26.79 ± 0.37	1.45
	6/41	8/237	2.28 ± 0.13	8.95 ± 0.31	18.00 ± 0.32	1.76
		12/355	2.81 ± 0.18	9.85 ± 0.25	19.05 ± 0.67	1.65
		16/474	3.96 ± 0.07	10.86 ± 0.01	20.43 ± 0.14	1.52
Clarke Cougar Cold Aerosol Generator	7.5/52	1/30	3.32 ± 0.29	14.00 ± 0.78	32.57 ± 6.08	2.08
		4/118	3.33 ± 0.11	14.28 ± 0.16	30.39 ± 0.56	1.89
		8/237	3.90 ± 0.36	17.73 ± 1.34	36.55 ± 2.32	1.84
		12/355	4.13 ± 0.38	20.53 ± 1.10	41.33 ± 2.03	1.81
		16/474	4.43 ± 0.04	23.14 ± 0.52	45.64 ± 0.98	1.78
		18/533	4.44 ± 0.47	23.30 ± 0.84	46.09 ± 1.40	1.79
		220/5,920	3.96 ± 0.10	22.88 ± 0.26	45.37 ± 0.63	1.81

and the ADAPCO Guardian 190ES showed decreases in the droplet size with increases in pressure at the same flow rate. These sprayers were different as a result of being able to control the flow rate and spray pressure independently. The other sprayers that did not have this independent control had increases in flow rate with increasing spray pressure, which resulted in lower droplet sizes. Sprayers for which pressure could be changed while maintaining constant flow rate typically showed smaller droplet sizes with increasing pressure. An exception to this trend was the ADAPCO Guardian 55ES, which showed larger droplet sizes with increases in pressure with the machine set at the same flow rate. It was observed that while the flow rate was maintained at a constant setting on the machine, it still increased with increasing pressure resulting in increased droplet sizes.

BVA oil sprays

Generally, for a given sprayer and set of operational settings, the BVA oil resulted in smaller droplet sizes than the water plus NIS. The VMDs across all sprayers tested with the BVA oil spray solution ranged from 3 to 220 μm (Tables 3, 4, 7, and 8) with the majority of the sprayers having VMDs between 10 to 30 μm. Similar to the results when spraying the water and NIS solution, for sprayers whose settings could be adjusted, as the flow rate increased (at constant pressure), the droplet size increased as well. Also similar to the water and NIS spray solution results, for sprayers whose pressure could be increased while maintaining flow rate, droplet size decreased as the spray pressure increased. An exception to this was the ADAPCO Guardian 55ES ULV sprayer, which had an increase in droplet size with an increase in spray pressure at the same flow rate.

DISCUSSION

Increases in vector-borne diseases and pest resistance as a result of changing macro- and microclimates (Sutherst 2004, Lehmann and Diabete 2008) will require a thorough understanding of current application equipment used for controlling vectors to ensure that efficient and effective application are made. The data presented help both current and future users of vector control equipment to select the most appropriate spray solution and sprayer setup for their specific spray application. For example, if an applicator is making a barrier application where the desired result is droplet impaction and retention on barrier surfaces with minimal drift, a sprayer that generates larger droplets (i.e., $D_{V0.1} > 40$ μm) would be selected. Were an application being made that called for lateral downwind movement of sprays to impact flying insects (Brown 1968), a sprayer with a VMD between 8 and 30 μm would be selected. The data from this work, along with previous and future studies, are being incorporated into a number of user databases and decision-making systems to provide quick access to droplet-size characteristics resulting from multiple types of equipment under a range of operational settings and spray formulations to support optimization of applied sprays.

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REFERENCES CITED

ASTM [American Society for Testing and Materials]. 2004, Standard E1620. Terminology relating to liquid particles and atomization. *Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International.

ASTM [American Society for Testing and Materials]. 2005, Standard E1260. Standard test method for determining liquid drop size characteristics in a spray using optical nonimaging light-scattering instruments. *Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International.

Brown AWA. 1968. Principles of dispersal in ground equipment and insecticides for mosquito control. *Amer Mosq Contr Assoc Bull* 2:11–19.

Haile DG, Mount GA, Pierce NW. 1982. Effect of droplet size of malathion aerosols on kill of caged adult mosquitoes. *Mosq News* 42:576–583.

Hoffmann WC, Walker TW, Fritz BK, Farooq M, Smith VL, Robinson CA, Szumlas D, Lan Y. 2009. Spray chararacterization of ultra-low volume sprayers typically used in vector control. *J Am Mosq Control Assoc* 25:332–337.

Hoffmann WC, Walker TW, Fritz BK, Gwinn T, Smith VL, Szumlas D, Quinn B, Lan Y, Huang Y, Sykes D. 2008. Spray characterization of thermal fogging equipment typically used in vector control. *J Am Mosq Control Assoc* 24:550–559.

Hoffmann WC, Walker TW, Martin DE, Barber JAB, Gwinn T, Smith VL, Szumlas D, Lan Y, Fritz BK. 2007a. Characterization of truck-mounted atomization equipment used in vector control. *J Am Mosq Control Assoc* 23:321–329.

Hoffmann WC, Walker TW, Smith VL, Martin DE, Fritz BK. 2007b. Droplet-size characterization of handheld atomization equipment typically used in vector control. *J Am Mosq Control Assoc* 23:315–320.

Ledson M, Matthews GA. 1992. Droplet spectra with thermal foggers. *Aspects Appl Biol* 33:125–30.

Lehmann T, Diabate A. 2008. The molecular forms of *Anopheles gambiae*: a phenotypic perspective. *Infect Genet Evol* 8:737–746.

Linley JR, Jordan S. 1992. Effects of ultra-low volume and thermal fog malathion, scourge and naled applied against caged adult *Culicoides furens* and *Culex quinquefasciatus* in open and vegetated terrain. *J Am Mosq Control Assoc* 8:69–76.

Matthews GA. 1996. Application of insecticides in dengue control. *Pesti Out* 7:24–30.

Mount GA. 1998. A critical review of ultralow-volume aerosols of insecticides applied with vehicle-mounted generators for adult mosquito control. *J Am Mosq Control Assoc* 14:305–334.

Rathburn CB Jr. 1972. Ultra low volume tests of malathion applied by ground equipment for the control of adult mosquitoes. *Mosq News* 32:183–187.

Rose RI. 2001. Pesticides and public health: integrated methods of mosquito management. *Emerg Infect Dis* 7:17–23.

Sutherst RW. 2004. Global change and human vulnerability to vector-borne diseases. *Clin Microbiological Rev* 17:136–172.

WHO [World Health Organization]. 2006a. *Equipment for vector control: specification guidelines*. Geneva, Switzerland: World Health Organization.

WHO [World Health Organization]. 2006b. *Pesticides and their application.* 6th edition. Geneva, Switzerland: World Health Organization.